ENGINEER - Vol. LV, No. 03, pp. [11-20], 2022

DOI: http://doi.org/10.4038/engineer.v55i3.7517

Compressibility Characteristics of Open Dumped Municipal Solid Waste in the Dry Zone of Sri Lanka

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Abstract: Primary compression is known to be the major component in the settlement mechanism of Municipal Solid Waste (MSW). Presented in this paper are results obtained using a modified large-scale oedometer describing the primary compression characteristics of MSW dumped at the Hambantota open dump site in Sri Lanka. Samples from varying depths were extracted from the dump site to evaluate the compressibility characteristics of MSW in order to expand the existing dump site to landfill. The dumping area was divided into two categories corresponding to the age of the fill. Compressibility and composition of old (10 years) and new (2 years) waste showed similar characteristics. One-dimensional confined compression tests were conducted for shredded MSW re-compacted at field densities. The compression index C_c was observed to vary from 0.15 to 0.27. However, after normalization by the initial void ratio e_o, the modified compression index C_c' varied in a narrow band between 0.08 and 0.11, signifying that C_c' is the more suitable parameter to predict primary consolidation settlement of solid waste dump sites.

Keywords: Compression index, dry zone, landfill, municipal solid waste, oedometer test

1. Introduction

Municipal Solid Waste (MSW) generation has increased in mammoth proportions in the past few decades. According to the World Bank review on solid waste management in 2016, global city residents and commercial institutions generated a staggering 2.01 billion tons of MSW per year [29]. Furthermore, with rapid population growth and urbanization, annual MSW generation is expected to increase by 70% from 2016 level to 3.4 billion in 2050. As such, the current average daily per capita generation of 0.74 kg MSW is further expected to increase with rapid urbanization of the globe [29].

The rise in generation of MSW has led to unplanned vertical expansion of MSW landfills and has resulted in an increasing interest on waste management and disposal. Where MSW is concerned, landfills are the most frequently used method of final solid waste disposal [1]. The vertical expansion of existing landfills is presently being undertaken in many cities around the globe due to social and political problems associated with identifying new landfill sites [2].

Consequently, stability of the waste mass is one of the major concerns associated with the design of landfill expansion. Past experience has shown that both vertical and lateral expansion of landfills can trigger waste mass instability. The Payatas landfill in Philippines, which eventually caused a flow slide in 2000 killing 330 persons, is one such example [3]. Similarly, a slide occurred in the large garbage dump site at Meethotamulla in Colombo of Sri Lanka on the 14th of April 2017 causing 32 deaths with eight more missing and affected a total of 1765 people [30]. On the other hand, lateral expansion may involve a large excavation adjacent to the side slopes of an existing landfill. The largest waste mass instability in the United States occurred in 1996 following lateral expansion of the existing Rumpke landfill in Ohio [4]. Java landfill in Indonesia [5] and the Dona Juana Landfill in Colombia [6] are two more examples of such landfill failures in recent history.

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Almost all the landfill failures in history have resulted from unplanned expansion of MSW landfills, either vertically or laterally. Settlement behaviour prediction is one factor that affects the design of MSW landfill expansions. In addition, prediction of the settlement of MSW in a landfill can aid in evaluating the integrity of the final landfill cover. Thus, evaluation of compressibility characteristics of MSW landfills is essential prior to designing any expansion.

Many models and theories have been proposed and studies have been conducted to predict the settlement of MSW landfills ([1], [7] - [15]). A considerable variation in MSW composition exists between different landfills and this creates difficulties in applying a constitutive model developed for one landfill to predict the settlement of another.

Quite similar to the global trend, high mounds of garbage are being piled up in Sri Lanka. Because it is a developing country constrained by inadequate funding, the most economical means of waste disposal is landfills. However, open dumps seem to be the most common practice of waste disposal in the country. Hambantota is a rapidly developing area in Sri Lanka, with infrastructure facilities being developed in order to make the area an economic hub in the south Asian region. The potential growth of the future floating population in the area is an imminent threat to the prevailing MSW management system. Development of an existing MSW open dump as a sanitary landfill is proposed as a means to maintain proper waste management in the area. Therefore, in order to alleviate catastrophic failures in the future, it is necessary to conduct studies on compressibility characteristics of MSW for proper design of expansion in existing landfills in Hambantota.

The conventional method of determining compressibility characteristics of soil using an oedometer apparatus, cannot be applied for testing MSW due to large particle sizes. Various research groups ([9], [10], [12], [15] - [20]) have used different techniques to determine the compressibility characteristics of MSW. However, most sophisticated techniques adopted by some researchers cannot be applied within the context of developing countries due to budget constraints. Thus, results of an experimental low-cost laboratory setup produced to evaluate the compressibility characteristics of MSW from the Hambantota dump site are presented in this paper.

2. Site Description and Sampling

The selected dump site at Hambantota is located in the Southern Province of Sri Lanka belonging to the south arid zone of the country. With a land area covering 322.54 km^2 and a population of 55,289, the number of housing units in the Hambantota Municipal Council is 14,518 [31]. The daily generation of MSW within this area is about 20.4 tons and only 9.9 tons is collected and dumped at the Hambantota open dump site located about 5 km to the north of Hambantota city [21].

Figure 1 illustrates the layout of the existing dump site at Hambantota alongside the Hambantota - Gonnoruwa main road. The dump site consists of two key areas based on the age of waste fill. The old waste (B) was around 10 years old whereas new waste (C) was approximately 2 years old at the time of testing. In addition, the site has an old waste area (A), adjacent to the existing dump site, which is approximately 15 years old. The dump site consists of a composting facility to utilize the large amount of organic waste arriving at the dump site. It is the usual practice that new waste is always pushed towards the old waste area (B) to acquire space for new waste dumping. Thus, even though area (B) is categorized as old waste, it is a mixture of old and new waste. Further, most of the waste in the old waste area (B) is burned. This is a very common practice in almost all open dump sites in Sri Lanka. An elephant fence (H) surrounds the existing dump site to protect it from wild elephants.

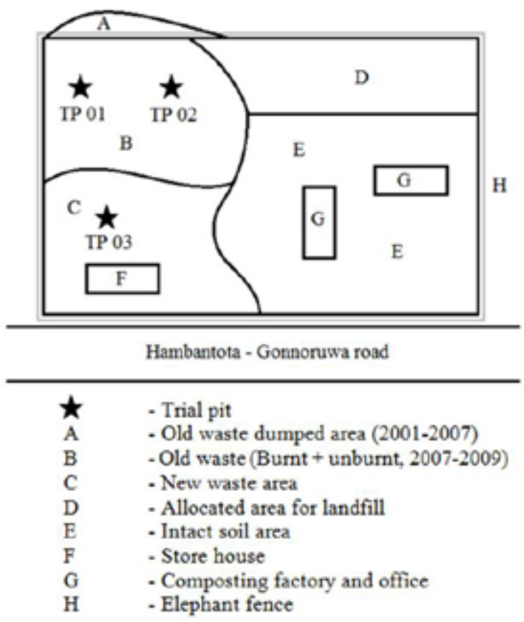

Figure 1 – Layout of the Existing Dump Site

Waste samples for the research study were obtained from three Trial Pits (TP) as shown in Figure 1. TP01 and TP02 represent the waste collected from old waste area, while TP03 is in the new waste area. Samples were extracted from the dump site by box sampling, using 0.3 x 0.3 x 0.3 m steel boxes as depicted in Figure 2. The method adopted made it possible to recover relatively undisturbed samples containing larger particles from the waste dump site while retaining its natural moisture content. Because the open dump site is relatively new, it was found that below about 1.0 – 2.0 m of excavation in-situ soils are present. Thus, undisturbed samples using steel boxes were obtained at depths of 0.5 m and 1.0 m from the existing ground surface.

With a low annual rainfall fluctuation between 500 mm and 775 mm [31], the waste dump site remains parched for most of the year. This was evident in the absence of the water table when MSW samples were excavated from the site.

Figure 2 – Box Sampling

3. Laboratory Testing Program

3.1 Compression Test Setup

A specially fabricated low cost, large scale oedometer setup was used to conduct confined compression tests in the laboratory on the waste samples collected. Primary compression of the waste samples, the main parameter in landfill settlement, as confirmed by [15], was tested using the above apparatus in this research study. The time dependent secondary compression is beyond the scope of this project. Figure 3 illustrates the cross section of the large scale oedometer apparatus used to measure 1-D compression of waste samples in this research study.

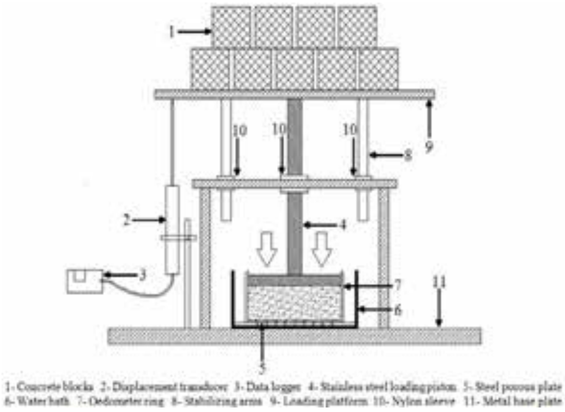

Figure 3 – Cross Section of Experimental Setup

Referring to Figure 3, the apparatus is supported on a firm metal plate (11) that was bolted to the ground to provide a level base. The water bath (6) was secured in position using a nut and bolt mechanism. The slotted steel porous plate (5) and the oedometer ring (7) were placed in the water bath in such a way that alignment with the stainless-steel loading piston (4) was perfect. Further, the mechanism was arranged to drain the water from the sample through the porous plate to the water bath, facilitating singly drained conditions. The vertical stress was simulated by connecting the loading piston to a loading platform (9) held in position by four vertical stabilizing arms (8). The desired load was attained by placing concrete blocks (1) on the loading platform. Nylon sleeves (10) were placed at each piston location to facilitate free movement of the piston. Having a diameter of 200 mm and a height of 100 mm, the oedometer ring enabled samples with large particle sizes to be tested. A water bath facilitated full saturation of MSW samples prior to conducting confined compression tests, and the porous plate at the base meant that dissipation of excess pore water pressure during compression was allowed. Clogging of the porous plate was prevented by placing a filter paper over the porous plate. A linear voltage displacement transducer (2) connected to a data logger (3) was used to measure the settlement of the samples upon loading. The laboratory experiment setup used in this research study is depicted in Figure. 4. Hydraulic jacks were used to support the platform during the loading process. Prior to loading the sample, a layer of grease was applied around the piston to allow smooth movement upon contact with the oedometer ring.

Figure 4 – Laboratory Experimental Setup

3.2 Sample Preparation

Remolded samples were used to conduct confined compression tests. Preparation of the samples was done while maintaining the field densities of the open dumped MSW. The bulk unit weight (γ_{bulk}) of waste at different locations was directly calculated from the box samples collected. Table 1 summarizes the bulk unit weights and in-situ moisture contents of waste samples from different locations. Sample ID displayed in the table indicates the test pit location and depth of sample collected. For example, TP02 1.0 indicates location 2 of old waste collected at a depth of 1.0 m from the surface. The index properties reported in this paper were determined according to the current procedures established by ASTM for soil testing with some incidental modifications for waste. In-situ moisture content was calculated by keeping the waste sample in the oven under 60°C to avoid burning organic constituents [20]. Bulk unit weight was determined by measuring weight and volume of the waste sample in the sample box.

Table 1 – Bulk Densities and Moisture Content of MSW Samples Collected

Sample ID	γ_{bulk} (kN/m^3)	Moisture content (%)
TP01 0.5	12.81	17.70
TP01 1.0	11.11	36.20
TP02 0.5	12.89	28.34
TP02 1.0	13.69	37.43
TP03 0.5	9.17	28.94
TP03 1.0	10.89	31.99

The sample preparation method adopted in this study is similar to that adopted by [1], [12], [17], [19], [20], where shredded MSW samples were compacted into the oedometer ring while maintaining field density. The reasoning behind shredding MSW is that collected MSW consisted of large objects and particles that cannot be used directly in the test setup. Samples were reconstructed with air-dried waste, and particles larger than 9.5 mm were shredded to minimize the interference of larger particles with the apparatus. Air drying was selected over oven drying to avoid physical deformation of particles in oven drying. The effect of shredding can be justified when considering the particle size distribution of the waste samples, as shown in Figure 5.

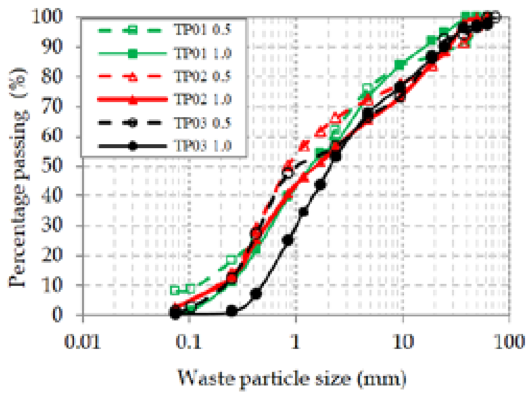

Figure 5 – Particle Size Distribution of Waste Samples

In this study, air-dried MSW samples were used prior to shredding to determine the particle size distribution of waste matter at each sampling point because shredded samples do not provide an accurate representation of the gradation of the MSW field condition. Figure 5 indicates that between 72% and 83% of the waste fraction was smaller than 9.5 mm in particle size in all samples. Hence, there wasn't any significant effect in usage of shredded samples for the compression test in this research because only 17–28% of the waste body is greater than 9.5mm.

3.3 Confined Compression Test

A staged loading method was adopted during the test inducing stresses of 16 kPa, 29 kPa, 60 kPa, and 120 kPa. The first load of 16 kPa was applied by the self-weight of the loading platform and the piston. Each loading stage was maintained for a period less than 24 hours. However, the period of each cycle relied mainly on the increment of settlement over time. When the compression was found to be negligible compared to the instantaneous settlement occurring at the beginning of loading, which was observed even before reaching 24 hours, the next load was applied. A maximum vertical stress of 120 kPa was maintained to replicate the stress resulting from a waste mound 8.0–10.0 m high.

4. Results and Discussion

4.1 Waste Composition

Figure 6 shows the composition of solid waste at the Hambantota Municipal Council dump site as a fraction of dry mass. Both new waste (TP03) and old waste (TP01 and TP02) consist of materials of gravel size (particle size greater than 4.75 mm) and smaller. The high concentration of gravel and other particulate matter in both new and old waste may be due to the practice of constantly bulldozing dumped waste towards the old waste area from the new waste area, which also results in mixing waste with soil. Consequently, the specific gravity of shredded MSW samples measured by water replacement method yielded results similar to that of soil [22]. Composition analysis of the waste at the Hambantota dump site conducted by Ohata et al. [22] yielded results agreeing with this study, even though a different categorization was adopted considering diversity of materials. The particle fraction (< 4.75 mm) was 61.8% for new waste and 59.1% for old waste, while the gravel content was 29.5% and 23.7% for new and old waste, respectively [22].

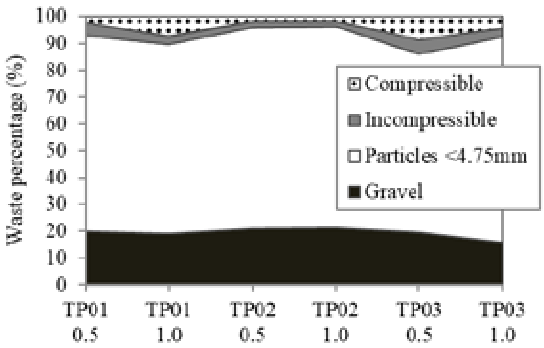

Figure 6 – Waste Composition at Hambantota Dump Site

The bulk unit weights of the waste samples collected ranged between 9.17 kN/m^3 and 13.69 kN/m^3, as a result of the dumping method in the dumped site. While agreeing to the results presented by Zhan et al. [2] and Chen et al. [18], these values were significantly higher than the values reported by some researchers ([10], [12], [17]), but were lower compared to results published by Pauzi et al. [13] and Huvaj-sarihan & Stark [23], which contained soil and construction debris in the waste bodies, respectively.

The percentage of mass described as particles with a size less than 4.75 mm is indistinguishable due to the decomposition that had taken place in the samples and thus were categorized by size. The composition of waste with age and location exhibited very little variation. In the categorization of waste, organic food waste was not distinguishable, although a major proportion of waste in Sri Lanka consists of food waste. The main reason behind such an observation could be due to the age of MSW collected. Sivakumar et al. [15] and Machado et al. [24] described food waste as easily biodegradable. Thus, it can be assumed that, by the time of sampling, most of the food waste had biodegraded. Furthermore, the reason for the low concentration of materials such as glass and metal is the scavenging induced by poverty in the developing world [25]. Compressible waste, namely paper, plastic, polythene, wood, garden waste, and fabric occupied 2–8% of the total waste. It is noted that a marginally higher percentage of incompressible waste exists in the new waste than in old waste.

4.2 Settlement-Time Behaviour

A typical settlement-time curve under stage loading of MSW is shown in Figure 7. It can be seen that MSW is subjected to instantaneous settlement followed by a gradual compression that differed with time. Such observations characterize a process of mechanical compression in the waste samples [12]. Because the samples were loosely compacted at field densities, an initial settlement was observed due to self-compaction of MSW upon saturation of the sample. A significant compression was observed in the first stage of loading and, in general, the settlements in subsequent stages were found to be significantly less, as shown in Table 2. This behaviour of MSW was observed irrespective of the age of MSW.

Table 2 – Settlement of MSW Samples under Staged Loading

Sample ID	Depth (m)	Settlement of stage (mm)				
		Initial	1	2	3	4
TP01 (Old)	0.5	16.9	7.6	1.6	4.7	2.2
	1.0	8.8	4.4	1.6	3.9	3.8
TP02 (Old)	0.5	15.4	9.4	2.3	2.0	3.4
	1.0	10.1	1.8	2.2	2.6	2.5
TP03 (New)	0.5	17.9	14.0	3.2	2.8	2.7
	1.0	15.8	8.8	2.9	2.7	1.9

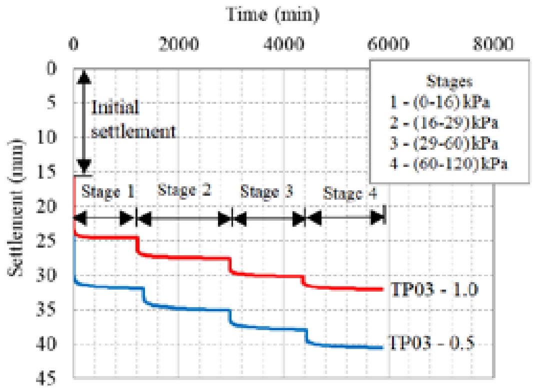

Figure 7 – Settlement-time Curve of New Waste (TP03)

The primary compression, as explained by Grisolia & Napoleoni [26], consists of an immediate decrease in the macro porosity caused by the rearrangement of deformable particles, followed by the compression of individual deformable particles, which lasts only about 200–300 minutes. Similar results were obtained in this study despite the fact that each loading stage was maintained for more than 1000 minutes. Further, as illustrated in Table 2, the initial settlement upon saturation and initial compression of new waste were higher than that of old waste. Results also indicated that the initial settlement at 0.5 m depth is significantly higher than that at 1.0 m depth. This behaviour can be explained by the fact that buried waste has a lower compressibility in comparison to waste on the ground surface which is not subjected to high overburden stresses. The first stage of loading in MSW samples demonstrated settlement behaviour is remarkably similar to that of soils. Figure 8 depicts the typical time differed settlement recorded in MSW samples at 16 kPa stress, after the initial settlement of samples. This MSW compression behaviour seemed to diminish in subsequent loading stages.

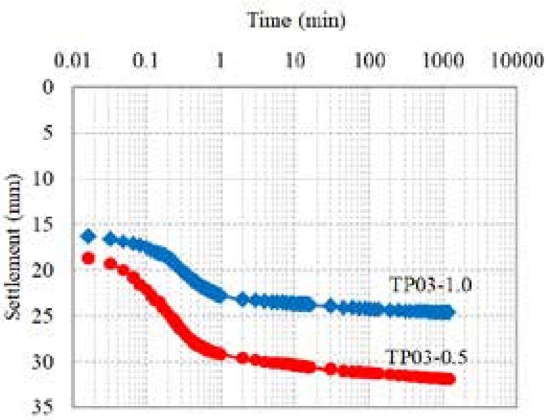

Figure 8 – Settlement-time Curve of First Stage of Loading (TP03)

4.3 Void Ratio

The compressibility characteristics of MSW are highly dependent on the voids existing in the waste body. The variation of void ratios in the MSW samples with increasing vertical stress is shown in Figure 9. The initial void ratios (e_0) of the test specimens ranged between 0.89 and 1.54 (Table 3). These observations were considerably lower than the values reported by Zhan et al. [2], which varied between 1.24 and 5.78. Although MSW is inherently a porous medium, the waste collected at the Hambantota dump site demonstrated low void ratios resulting from its peculiar composition. Because over 70% of the waste matter consisted of particles less than 4.75 mm (Figure 6), it can be argued that the smaller particles filled the spaces among larger particles and allowed for a tight arrangement of particles, which in turn reduced the initial void ratio.

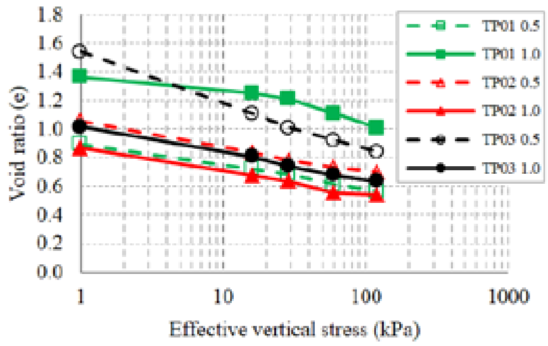

Figure 9 – Variation of Void Ratio with Vertical Stress

4.4 Volume Compressibility

For better understanding of MSW settlement behaviour, coefficient of volume compressibility, m_v, was calculated for each stage of loading for all the samples tested. Depicted in Figure 10 is the coefficient of volume compressibility of MSW plotted against increasing vertical stress. It is noted that the waste samples have slightly higher m_v values (0.0029–0.0107 m^2/kN) at a low vertical stress ($16kN/m^2$), whereas the volume compressibility variation has been narrowed to lower values (0.0003–0.0008 m^2/kN) upon reaching a high vertical stress (120 kN/m^2). Since MSW samples were compacted at field densities, which means a considerable amount of voids is present, particles rearrange at low stress levels, and calculated m_v values plummet. Because the volume compressibility is governed by the initial void ratios of samples, a considerable fluctuation in m_v values among samples can be observed at the 16 kPa stress level. It is evident that fresh waste has higher initial volume compressibility than old waste due to the presence of high amounts of organic matter. Similarly, waste at shallow depth shows higher volume compressibility than that at greater depth due to lower overburden pressure. Initial compression is followed by a mechanical deformation (physical deformation) of particles at higher stress levels. At higher stress levels, it can be observed that m_v values of MSW samples have converged to a similar value irrespective of the age of the waste samples.

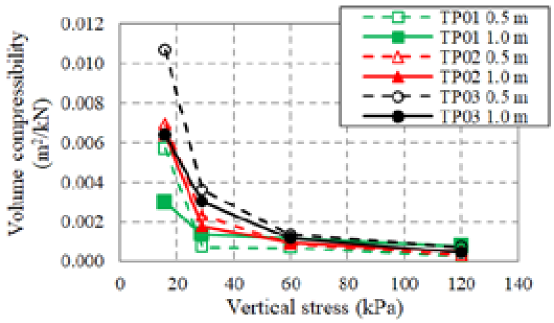

Figure 10 - Variation of Volume Compressibility of MSW

4.5 Compression Index

The compressibility of a porous medium is commonly expressed in terms of the primary compression index, C_c, in engineering practice. The compression curves for the MSW samples obtained from laboratory experiments are presented in Figure 9. The pseudo-yielding stress, which is defined as the pressure corresponding to the inflection point in the compression curve, is only seen in the old waste at 1.0 m depth and is equal to 16 kPa. The primary compression index is defined as the gradient of the post yielding curve, and corresponding C_c values of MSW samples tested are depicted in Table 3. Primary compression in a MSW sample occurs due to rearrangement of particles by reducing macro porosity and physical deformation of particles ([12], [16], [18], [19]).

It can be seen that C_c values varied from 0.15 to 0.27, which are considerably lower than the C_c values between 0.4 and 0.8 reported by Gabr and Valero [27]. However, there is a general trend of C_c decreasing with depth. Old waste consists of burned waste as well as decomposed waste, resulting in a lower compressibility. The variation of C_c over e_o for all samples tested is illustrated in Figure 11. It can be seen that all data points can be approximated to a straight line going through the origin ($C_c = 0.18e_o$). This line is slightly above the lower limit ($C_c=0.15e_o$) suggested by Sowers [28], which corresponds to waste with low organic content. All the data points obtained in this study fall within the limits suggested by Sowers [28], but do not agree with the limits suggested by Chen et al. [18] for waste of a similar age to that from this study. This is owing to the low compressibility of MSW at the Hambantota dumpsite resulting from its bizarre composition.

Table 3 – Compressibility Characteristics of MSW Samples

Sample ID	C_c	$C_c/(1+e_o)$	e_o
TP01 0.5	0.19	0.10	0.89
TP01 1.0	0.27	0.11	1.36
TP02 0.5	0.18	0.09	1.05
TP02 1.0	0.15	0.08	0.87
TP03 0.5	0.26	0.10	1.54
TP03 1.0	0.21	0.10	1.02

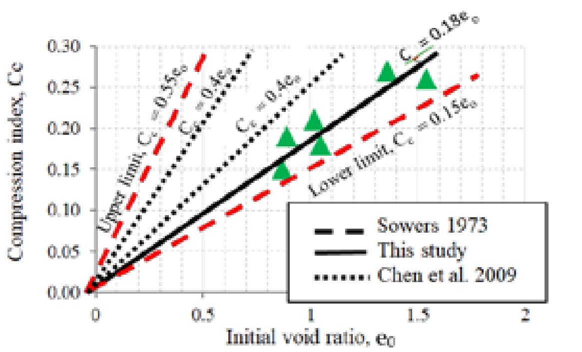

Figure 11 - Variation of Compression Index Over Initial Void Ratio

The effect of initial void ratio on compression index can be expressed in terms of modified compression index, $C_c' = C_c/(1+e_o)$. The variation of C_c' in all waste samples tested is shown in Table 3. Even though the value of C_c is highly scattered among samples, C_c' varies in a significantly narrower band (0.08–0.11), indicating that the compressibility is vastly dependent on the initial void ratio of MSW. The reason for attaining such low C_c' values in this study can be related to low initial void ratios and the large content of incompressible grit and gravel material present in the waste. The higher percentage of grit and other particulate matter in the waste tested is a result of the practice of dumping road sweepings in the dump site.

From the above results, it can be deduced that use of a single value of C_c to calculate the primary consolidation settlement is not constructive because C_c is highly dependent on the age and initial void ratio of the MSW.

Nevertheless, with the modified compression index C_c', the primary consolidation settlement of a waste body can be predicted fairly accurately because C_c' varies in a very narrow band.

5. Conclusions

Compressibility characteristics of new and aged MSW samples collected from the Hambantota open dump site (Sri Lanka) were determined using a low cost, locally fabricated confined compression test apparatus. Based on the results of the tests conducted, the following conclusions can be derived.

1. MSW at Hambantota Municipal council mainly consists of material of gravel size and smaller. Although a major portion of the waste in Sri Lanka consists of food waste, organic food waste was not distinguishable during the experiment because food waste had biodegraded by the time waste was collected.
2. The MSW samples showed different bulk unit weights ranging from 9.17 kN/m^3 to 13.69 kN/m^3, which are a result of waste mixing with soil in the dumping process.
3. MSW demonstrated considerably low void ratios (0.89–1.54) resulting from its peculiar composition.
4. The coefficient of volume compressibility, m_v, calculated for MSW samples representing two different ages showed scattered behaviour at low stress levels, where m_v varied from 0.0029 to 0.0107 m^2/kN. However, at higher stress levels, variation of m_v narrowed to values between 0.0003–0.0008 m^2/kN. This indicates that MSW at the Hambantota dump site showed similar compressibility at higher stress levels irrespective of age.
5. The combination of unusual waste composition and low initial void ratios led to low compression index values in the waste samples tested, ranging from 0.15 to 0.27, and the modified compression index ranged from 0.08 to 0.11. Use of the modified compression index is recommended in calculating the primary settlement of landfills because it demonstrates a more predictable behaviour. Settlement behaviour of MSW samples was in agreement with mechanisms explained in the literature ([12], [26]). However, all MSW samples showed an unusual behaviour in which an initial settlement of the sample was observed upon saturation. This settlement was more pronounced for new waste in comparison with old waste (Table 2). A similar behaviour may be expected in the loosely compacted waste dump at Hambantota under heavy precipitation.

Acknowledgement

This research work was supported by Science and Technology Research Partnership for Sustainable Development (SATREPS) project funded by the Japan International Cooperation Agency (JICA) and Japan Science and Technology Agency (JST). The support given by geotechnical laboratory staff of University of Ruhuna in carrying out laboratory experiments is gratefully acknowledged.

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